Turbulence in a complex plasma

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German Aerospace Center (DLR)

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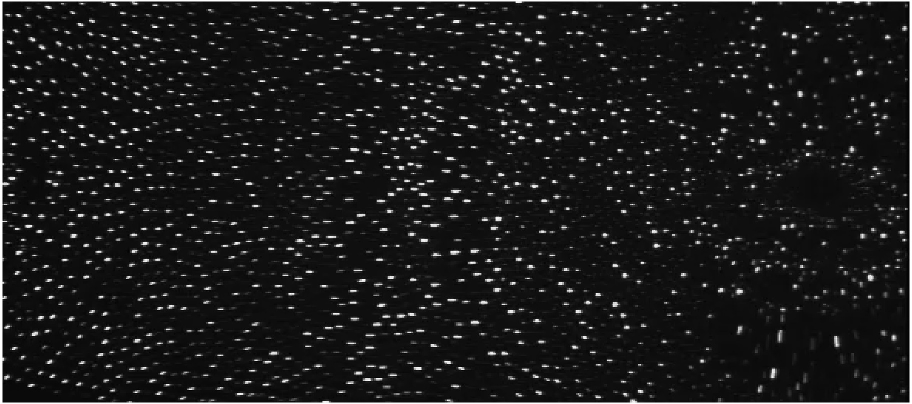

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Experiment

Signatures of Turbulence

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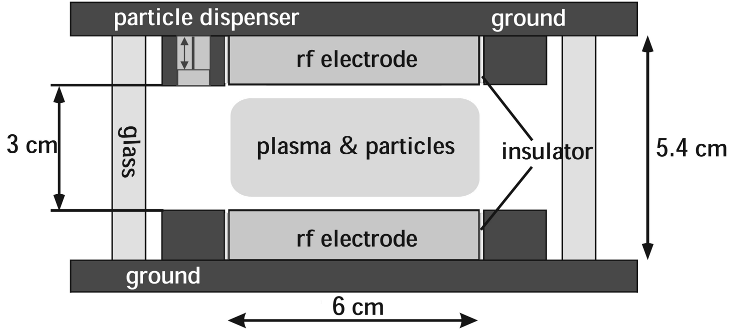

capacitively coupled plasma chamber

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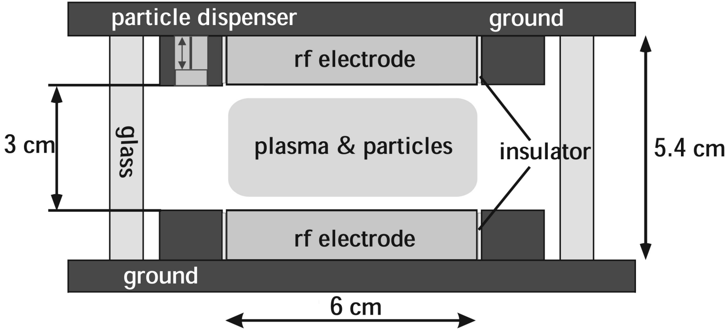

RF voltage on electrodes

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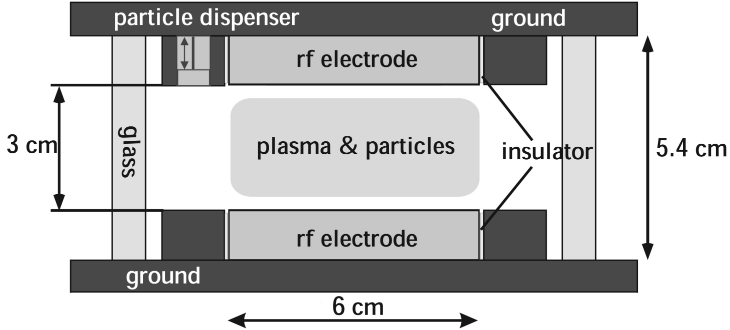

inject microparticles via dispensers

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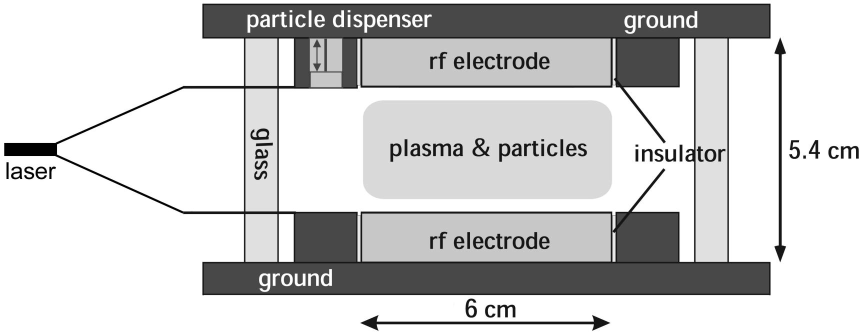
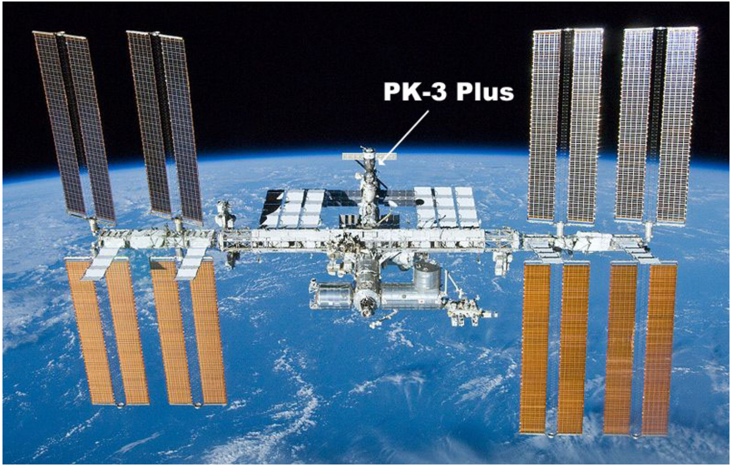


illuminate with laser from the side, trace particles

The PK-3 Plus Laboratory was hosted on the ISS from 2005 – 2014.



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ISS014E05960

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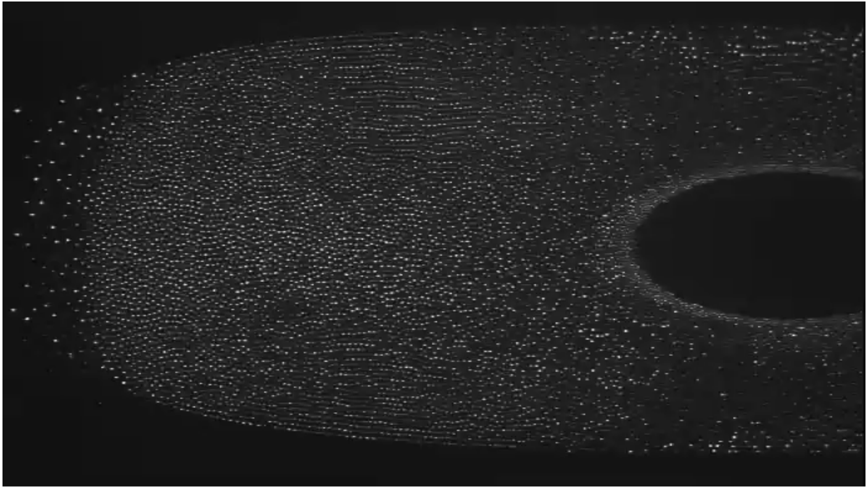
The system is often in a fluid state. Then vortices can form.



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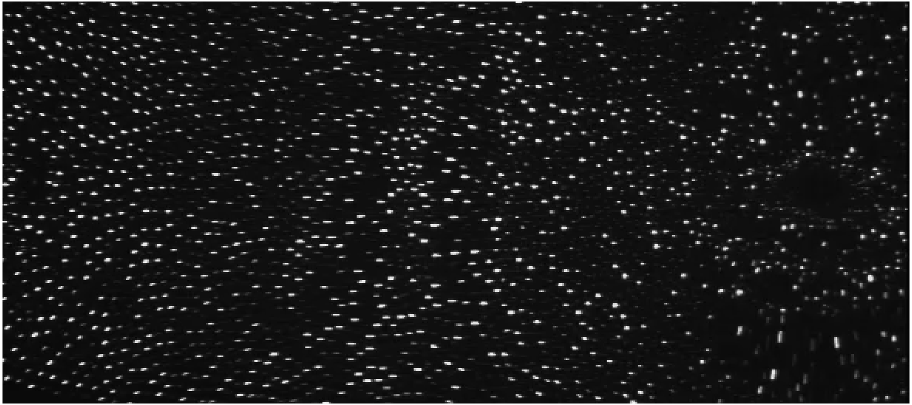
A heartbeat instability causes waves and oscillons.



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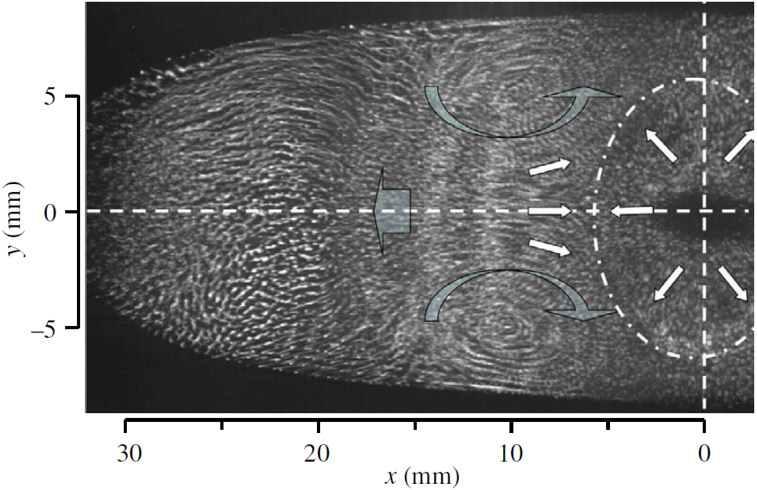
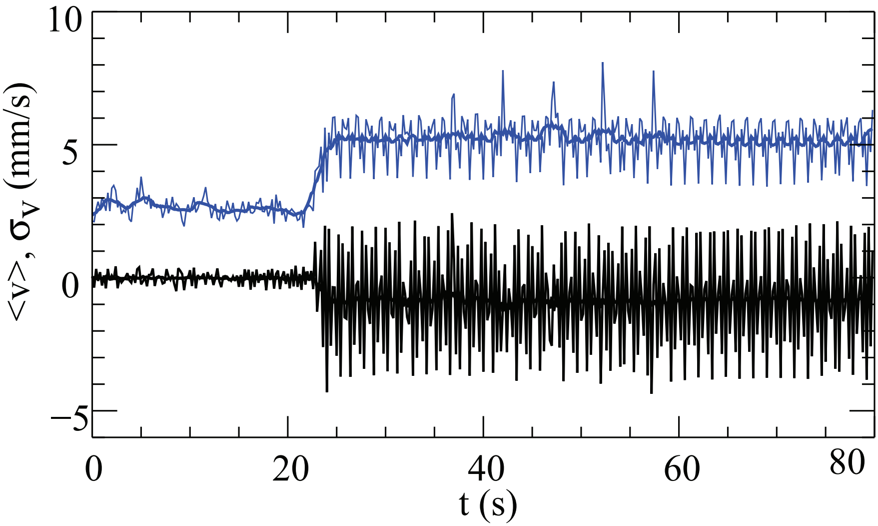
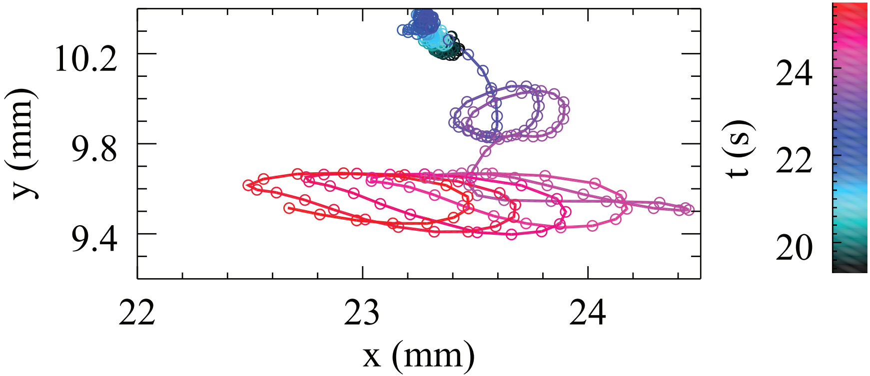


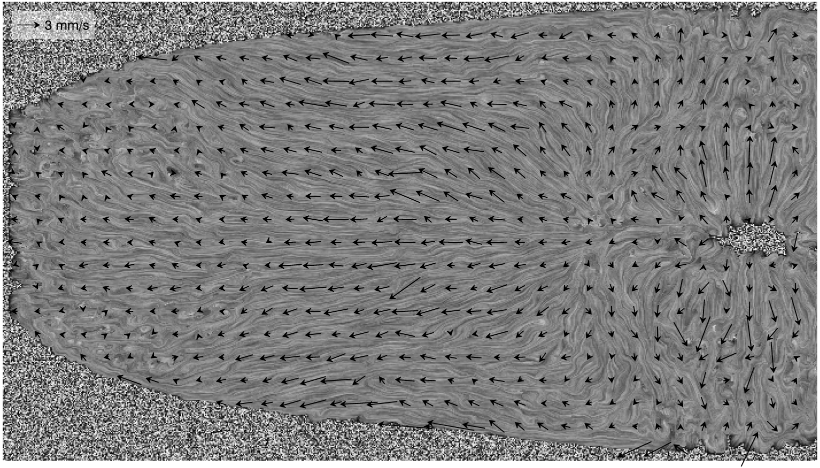
The instability causes a drift and heating of the particles.



The particles begin to oscillate.



The flow field is quite complicated.



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The Reynolds number determines the character of a fluid flow.

$$\mathcal{R} = LV/\nu$$

L: characteristic length
V: characteristic velocity
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$\mathcal{R} = LV/\nu$

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ν small, $\mathcal{R}$ large: nonlinear effects dominate, e.g. small scale movement develops, which leads even smaller scale movement, ...

The Reynolds number determines the character of a fluid flow.

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The Reynolds number in complex plasmas is very low.

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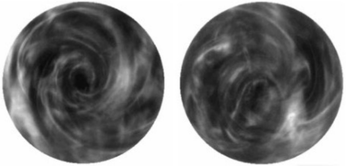
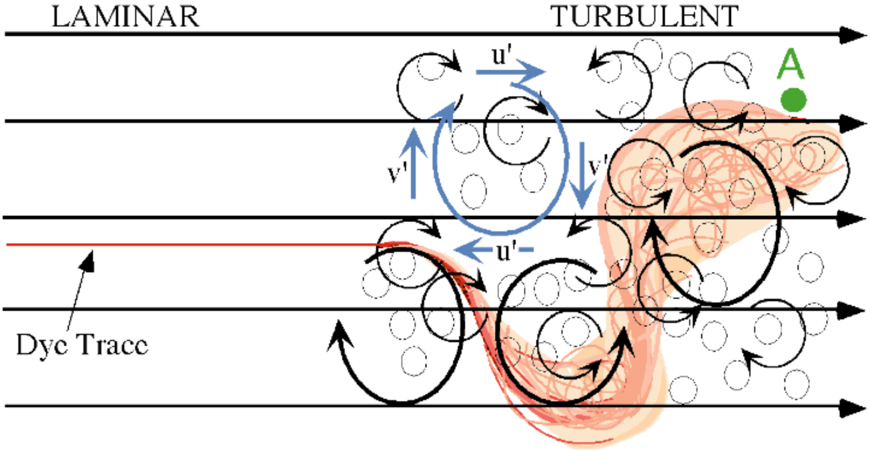


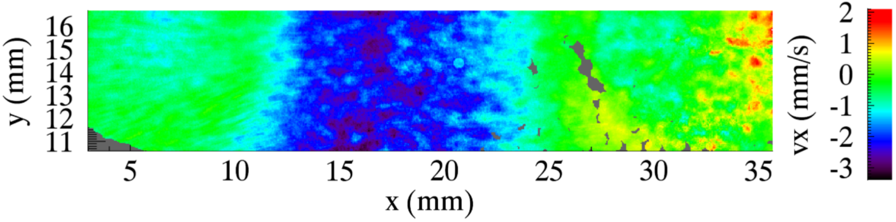
polymer solution with $\mathcal{R} = 0.7$
Groisman and Steinberg, Nature (2000)

Turbulence is a superposition of movement on many scales.

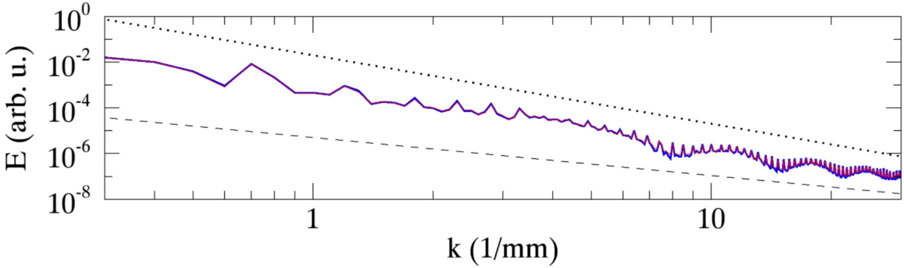


NEPF Lab, MIT

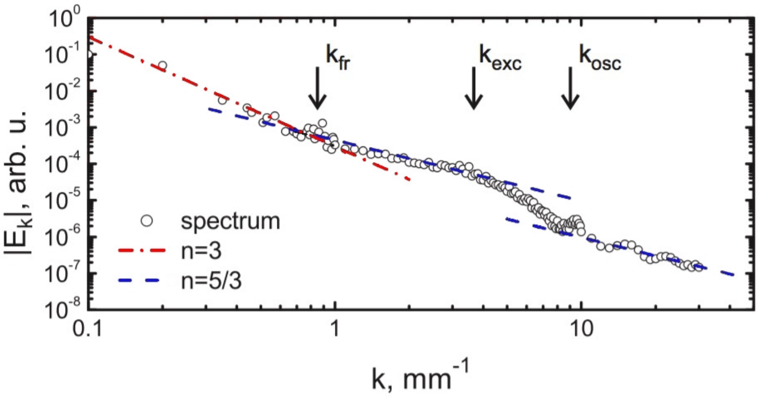
We calculate velocity maps.



Care needs to be taken to make sure that holes in the velocity maps do not influence the energy spectra.



The energy spectrum is dominated by three wave numbers.



$k_{\mathrm{fr}} = \frac{\gamma_{\mathrm{damp}}}{2C_{\mathrm{DAW}}} \approx 0.84\,\mathrm{mm}^{-1}$ scale defined by friction, transition at $k < k_{\mathrm{fr}}$ to $E_k \propto k^{-3}$ caused by friction

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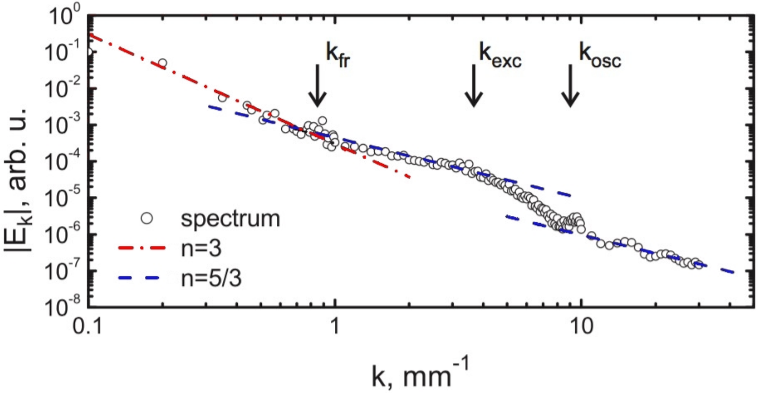

$k_{\text{exc}} = \frac{2\pi f_{\text{HB}}}{c_{\text{DAW}}} \approx 2.7\,\text{mm}^{-1}$ scale defined by heartbeat

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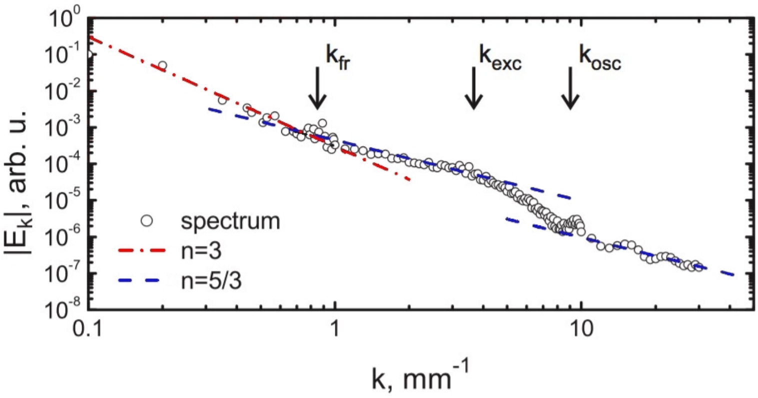
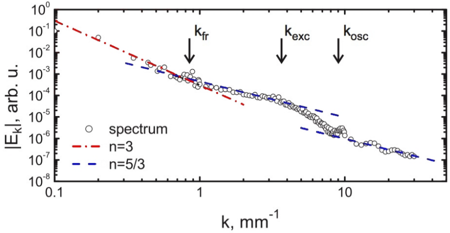


$k_{osc} = \frac{2\pi}{w_{osc}} \approx 9.0\,\mathrm{mm}^{-1}$ scale defined by oscillons

modulational instability causes oscillons

The knee at k_{exc} resembles a double cascade predicted for forced turbulence.



external force input at k_{exc} leads to

- inverse cascade of kinetic energy to $k \ll k_{\mathrm{exc}}$ ($E \propto k^{-5/3}$)
- direct cascade of enstrophy to $k \gg k_{\mathrm{exc}}$ ($E \propto k^{-3}$)

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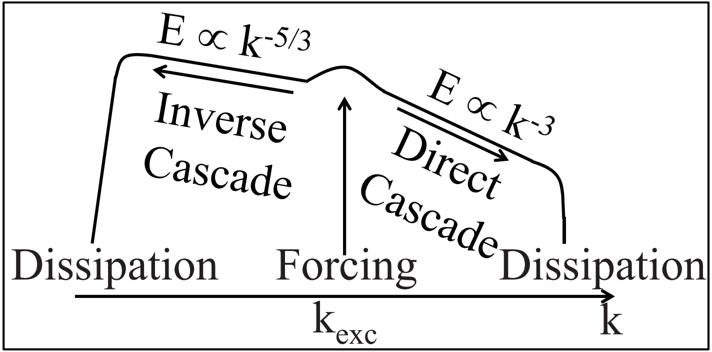
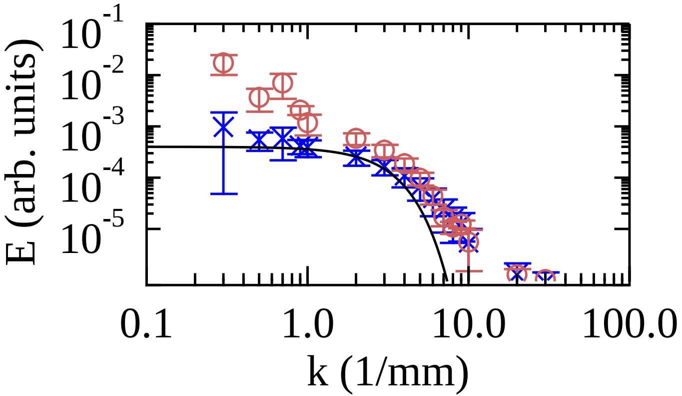


after Laurie et al. (2012)

The energy spectrum changes with the onset of the instability.



blue crosses: before / red circles: after the onset of the instability

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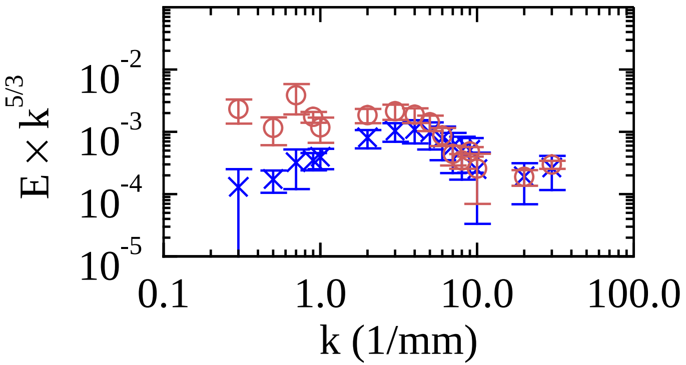

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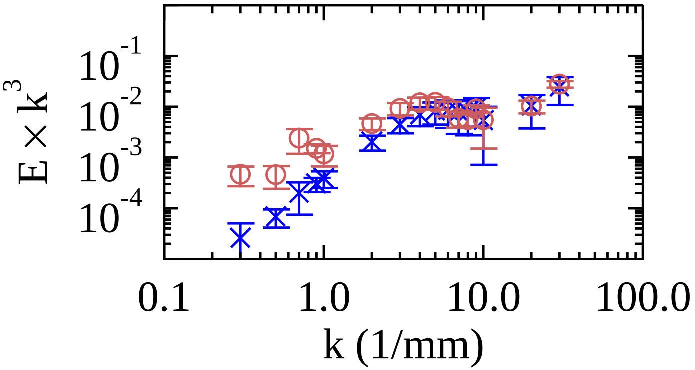

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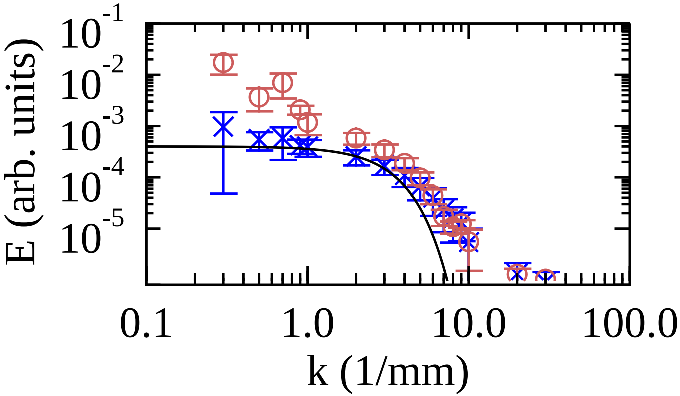
Fitting also results in the expected power-law exponents.



linear fit: $\log E = a - n \log k$ in both ranges separately

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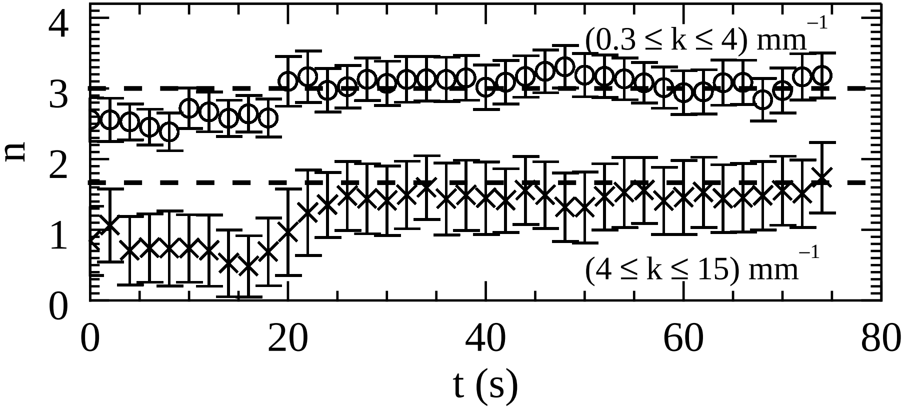

linear fit: $\log E = a - n \log k$ in both ranges separately

We define the reduced rates of energy and enstrophy transfer.

inverse cascade: $E = C\epsilon^{2/3}k^{-5/3} = \epsilon'^{2/3}k^{-5/3}$

ϵ: rate of cascade of kinetic energy / mass

direct enstrophy cascade: $E = \tilde{C}\eta^{2/3}k^{-3} = \eta'^{2/3}k^{-3}$

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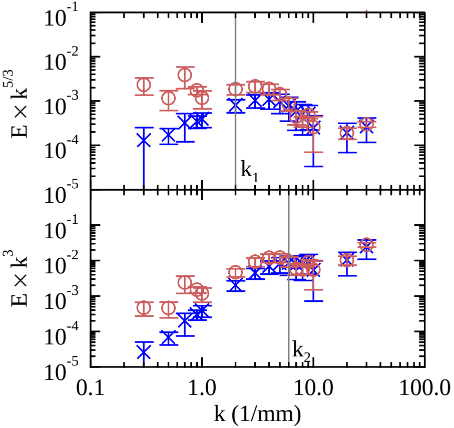
The reduced rates of transfer are calculated at fixed wave numbers.



$$E = \epsilon'^{2/3} k^{-5/3}$$
$$k_1 = 2\ \mathrm{mm}^{-1}$$

$$E = \eta'^{2/3} k^{-3}$$
$$k_2 = 6\ \mathrm{mm}^{-1}$$

The ratio of the reduced rates of transfer indicates the excitation wave number.

$$E = \epsilon'^{2/3} k^{-5/3}$$

$$E = \eta'^{2/3} k^{-3}$$

at $k = k_{\mathrm{exc}}$: $\epsilon'^{2/3} k^{-5/3} = \eta'^{2/3} k^{-3}$

$$k_{\mathrm{exc}} = \sqrt{\eta' / \epsilon'} == \kappa$$

We measure κ as function of time.

$$\kappa^2 = \eta'/\epsilon' = \left(\frac{Ek^3|_{k_2}}{Ek^{5/3}|_{k_1}} \right)^{3/2}$$

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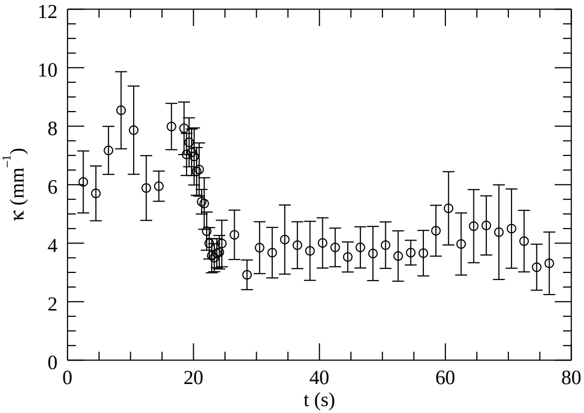
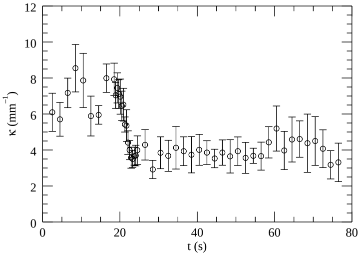


$$\kappa = k_{exc} = 3.9 \pm 0.5 \text{ mm}^{-1}$$

The excitation wave number determined in two separate ways agree.



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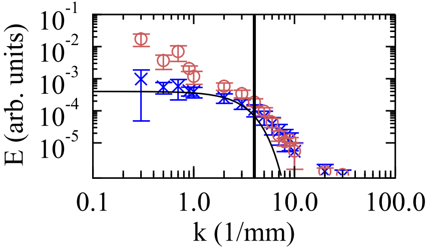

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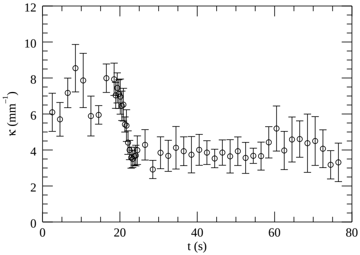

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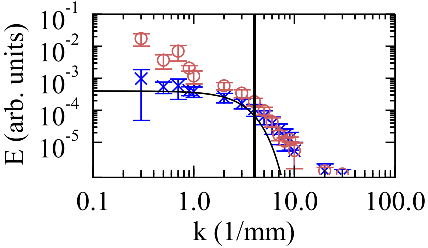

$$k_{exc} = \frac{2\pi f_{HB}}{C_{DAW}} \approx 2.7 \, \text{mm}^{-1}$$ scale defined by heartbeat

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observed a double cascade in an unstable complex plasma

change in spectrum when instability sets in, fitted power-law exponents agree with those predicted for double cascade

calculated excitation wave number by two methods

still a lot to do! e.g., study fluxes, movement of particles, . . .

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Conclusion

Thank you!

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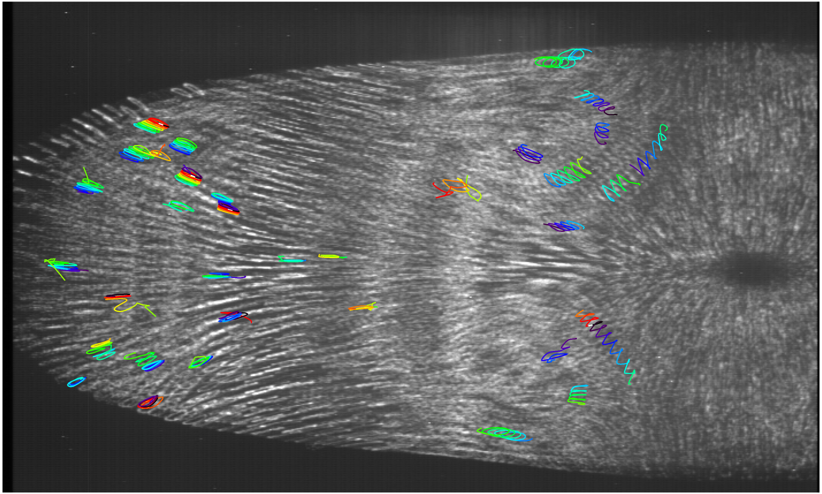
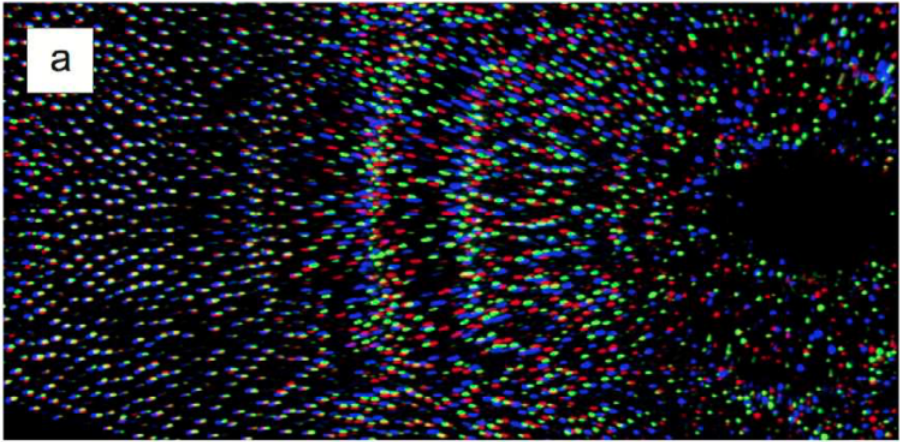
Sample Tracks



Oscillons - frames color-coded



Enstrophy is a common quantity used in turbulence research.

$$\Omega_{kl} = \left(\frac{1}{n} \sum_{i=0}^{n} \omega_i \right)^2$$

(k, l): grid cell coordinates
$\omega_i = (\text{curl } v)_i$: vorticity
n: number of particles in cell

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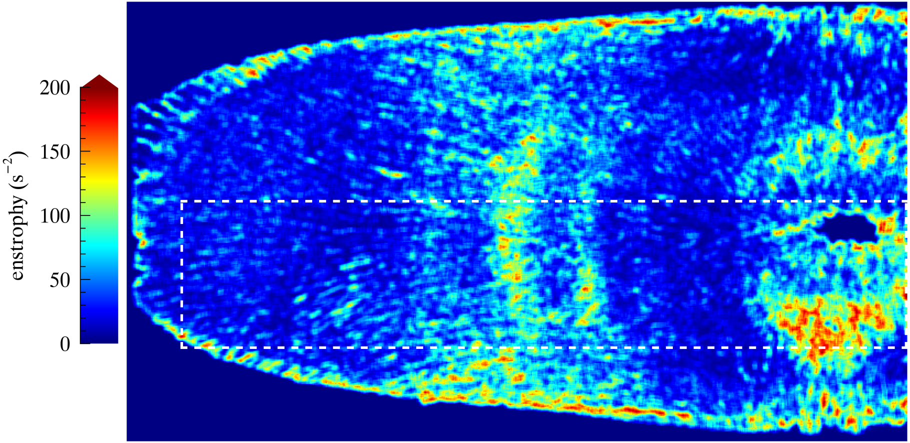
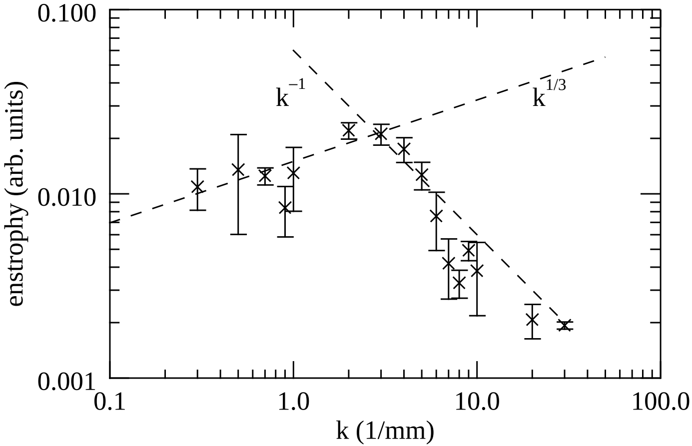
$\rightarrow$ potential density related to the kinetic energy that corresponds to dissipation effects in the fluid

Enstrophy map



Enstrophy spectrum



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